# Absolute VUV Radiometry with Silicon Photodiodes

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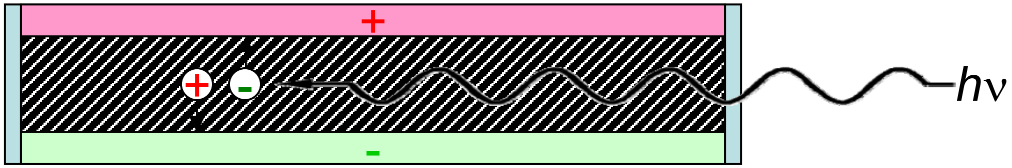
# X8a / U3c Radiometry Beamlines

- 50-6500 eV photons
  - 95-99% harmonic purity
  - 1-100 μW/cm$^2$ typical flux (~1 mm typical spot size)
  - Turbo-pumped high vacuum endstations
  - detector positioning automation
- Silicon diodes as calibration standards
  - "Self-calibration" method used
  - Verification performed with photoemission detectors, calibration at other light sources
  - Useful for other scientific applications?

# Ionization Detector

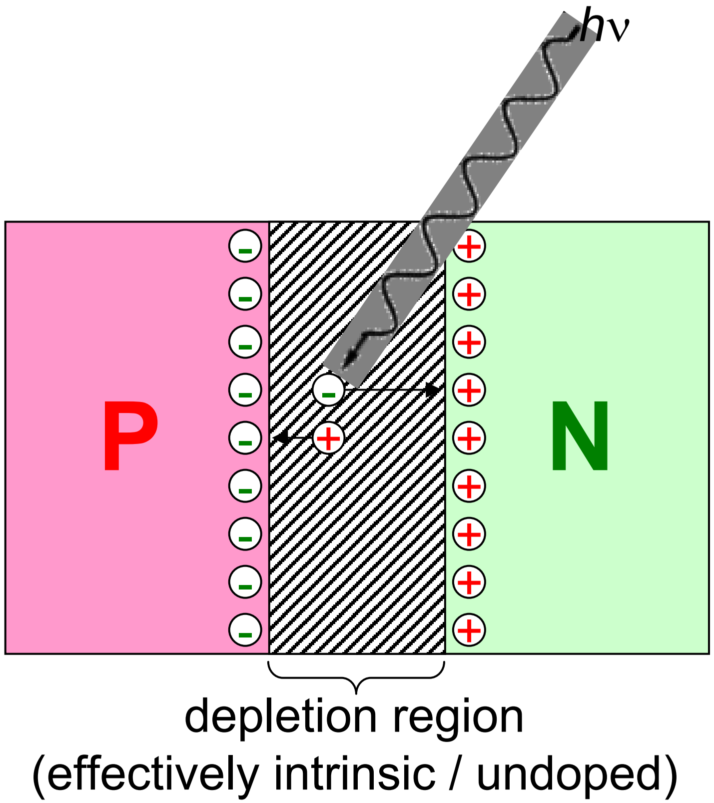


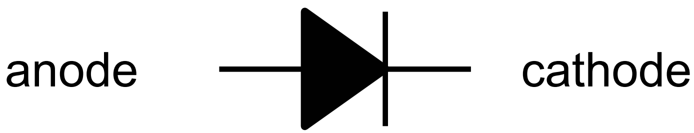

$$S = \frac{1}{w} e^{-t_{window}/\lambda_{window}} \left(1 - e^{-L_{active}/\lambda_{active}}\right)$$

**Requirements:**

- Known window absorption & thickness
- Known active length absorption & length
- Known mean ionization energy
- Ionizable insulator medium
- Unobstructed path for photo-injected charge carriers to reach collection electrodes

# Silicon Photodiode (PD)

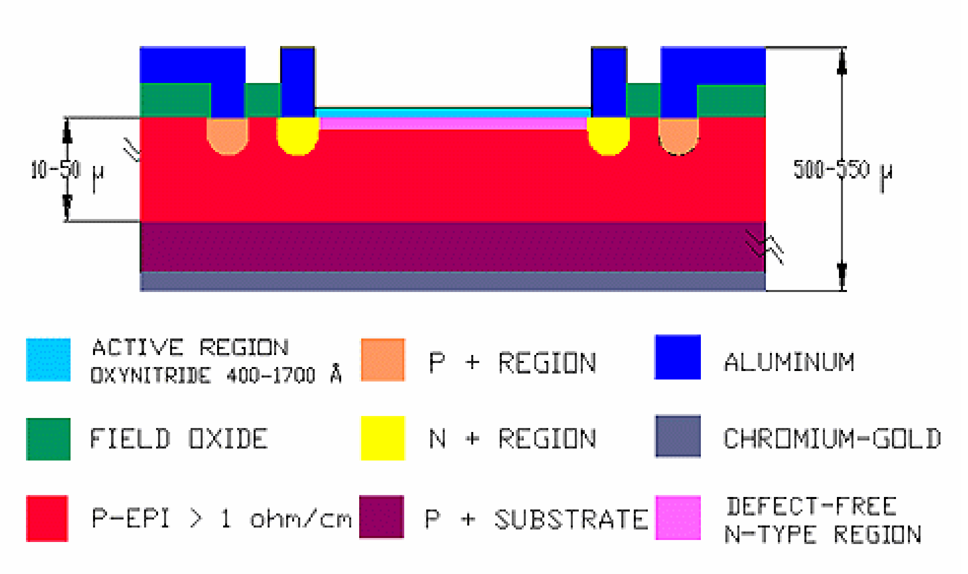



- Made of ***highly pure, crystalline silicon***
- Mean pair production energy ($w$) for ***silicon*** = ***3.66 ± 0.03 eV***
- Diode can be made to be ***self-depleting*** (full depletion without bias) to 50 μm, maybe more
- Low dark current (reverse leakage) at zero bias (< 1 pA), otherwise ***reverse current is proportional to number of photo-injected charge carriers*** ("photoconductive current mode")
- Bandgap = 1.14 eV (1.10 μm)

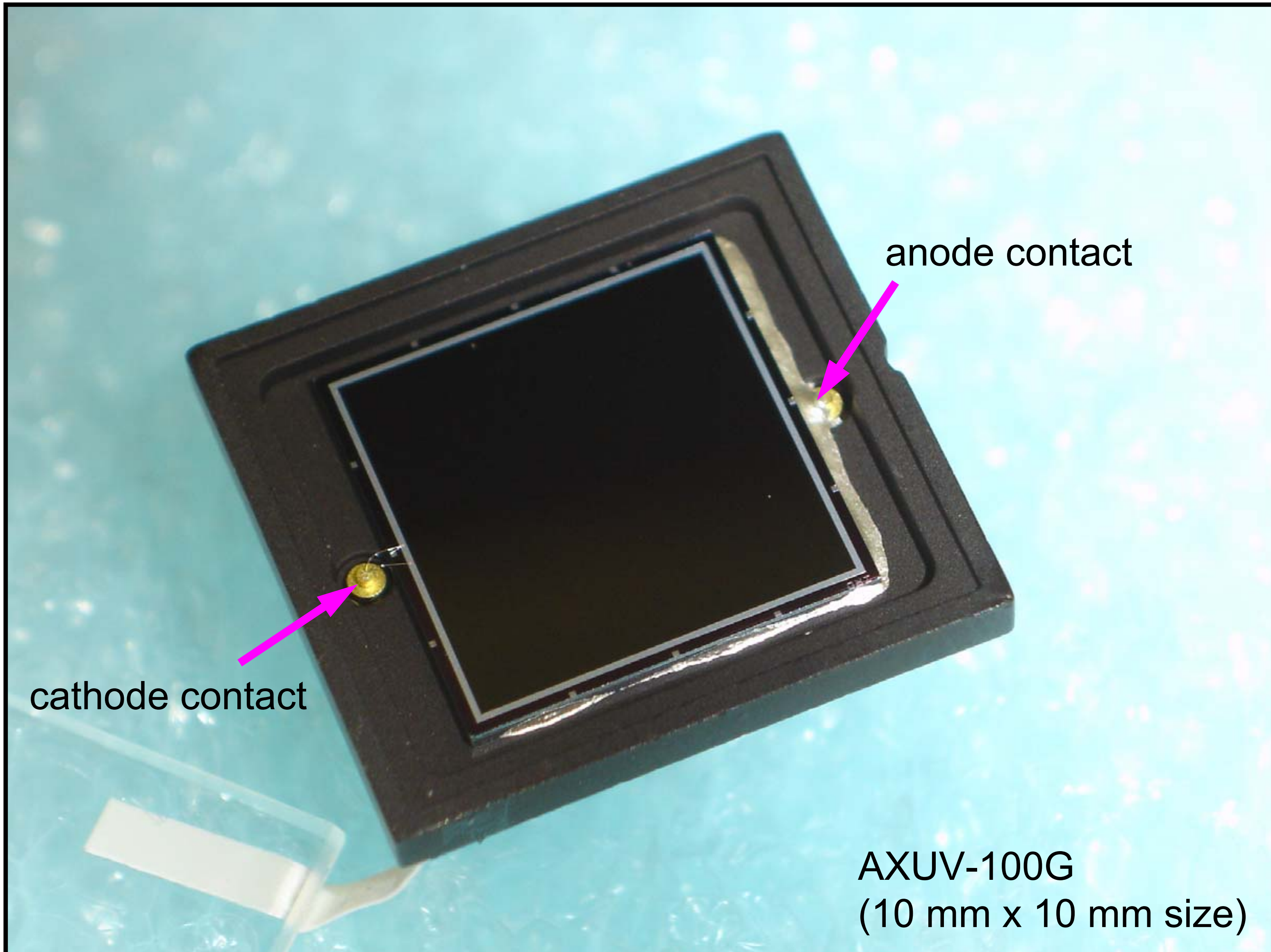
# The IRD PD

- N-on-P construction
- AXUV-G product has a ***thin (~5-7 nm) oxide window layer for maximum QE in the UV/EUV*** (oxynitride): “windowless” at 1 keV
- Standard active layer thickness is 25 µm
- In SXUV product, the oxide is replaced with silicide. PtSi, TiSi, and TaSi window layers are available upon request (PtSi is standard; nitric oxide ambient during processing essentially means TiSi = TiSiN) – this product is purportedly designed to mitigate damage due to radiation and moisture (oxidation, contamination) seen in SR applications
- Shunt resistance is variable from device to device (2 MΩ – 2 GΩ) and must be specified & tested

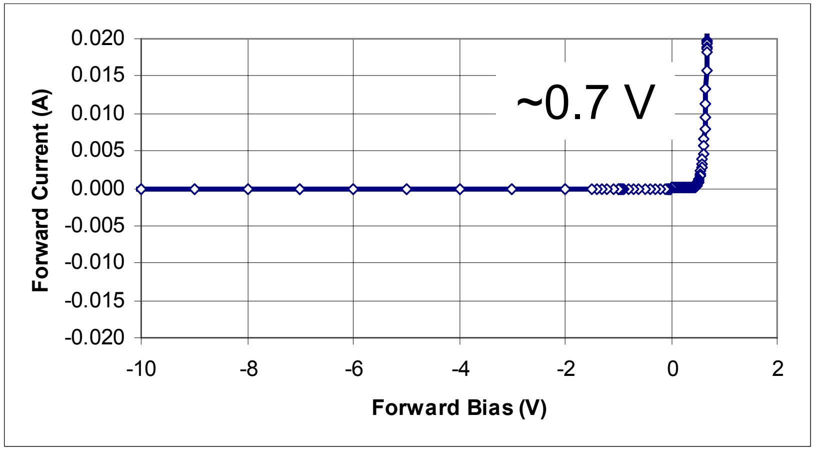


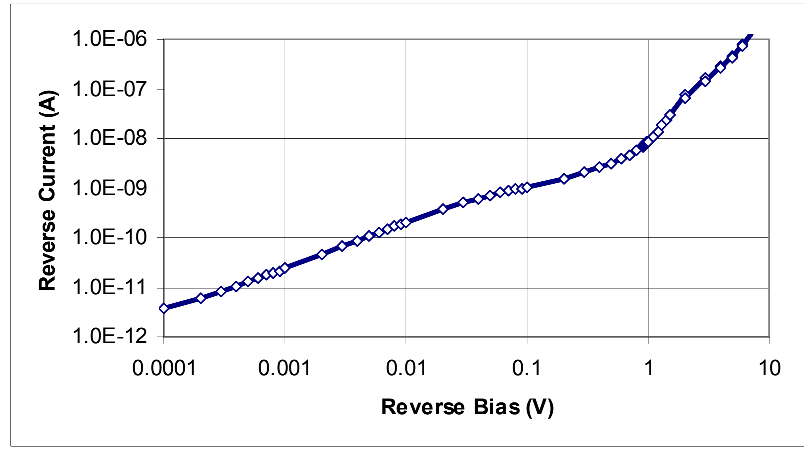

Other vendors include:
- Hamamatsu
- Perkin-Elmer

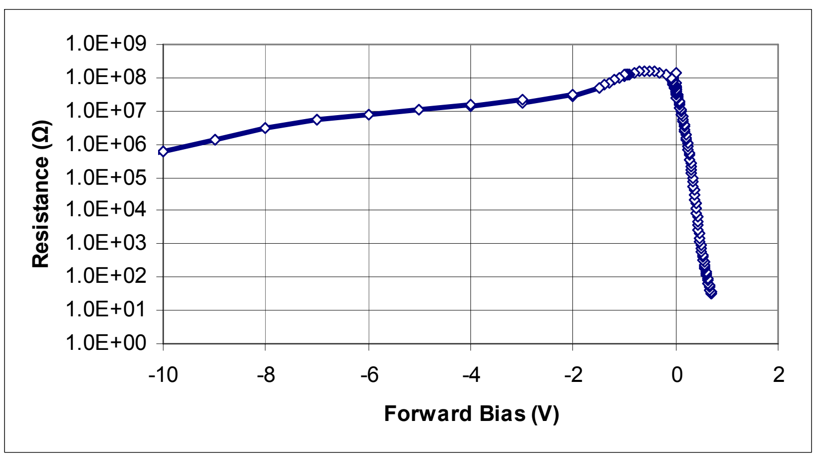
# The IRD PD

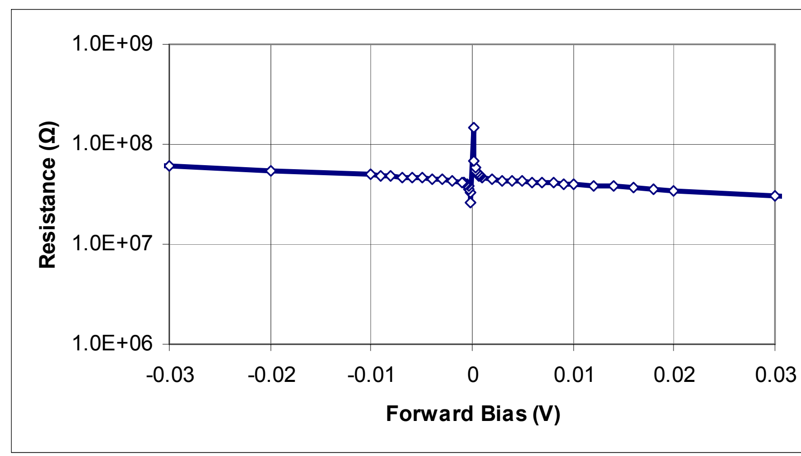


# PD I-V curves (dark)



# Importance of Shunt Resistance

**K617**

Table 2-9. Minimum Recommended Source Resistance Values in Amps

| Range | Minimum Source Resistance |
|---|---|
| All pA | 100GΩ |
| All nA | 100MΩ |
| All μA | 100 kΩ |
| All mA | 100 Ω |

**K6514**

*Table 4-2*
*Minimum recommended source resistance values*

| Range | Minimum Recommended Source Resistance |
|---|---|
| pA | 1GΩ to 100GΩ |
| nA | 1MΩ to 100MΩ |
| μA | 1kΩ to 100kΩ |
| mA | 1Ω to 100Ω |

**K6517A**

*Table 2-10*
*Minimum recommended source resistance values*

| Range | Minimum recommended source resistance |
|---|---|
| pA | 1 GΩ to 100 GΩ |
| nA | 1 MΩ to 100 MΩ |
| μA | 1 kΩ to 100 kΩ |
| mA | 1 Ω to 100 Ω |

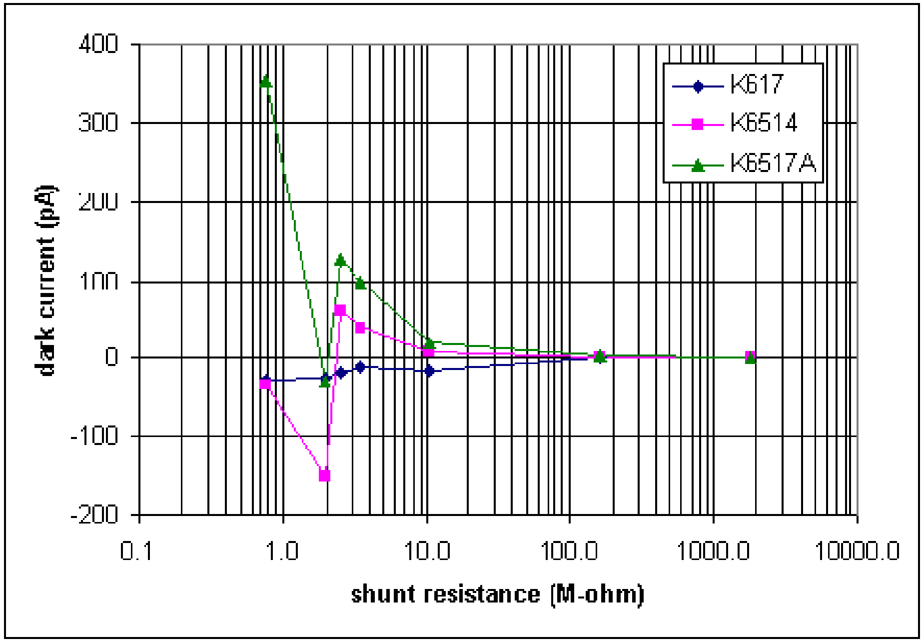
- Low shunt resistance makes the [dark] current depend on small ambient potentials
- Ammeter autoranging is slow when shunt resistance is low (10 s)
- Response time goes like RC for the PD:

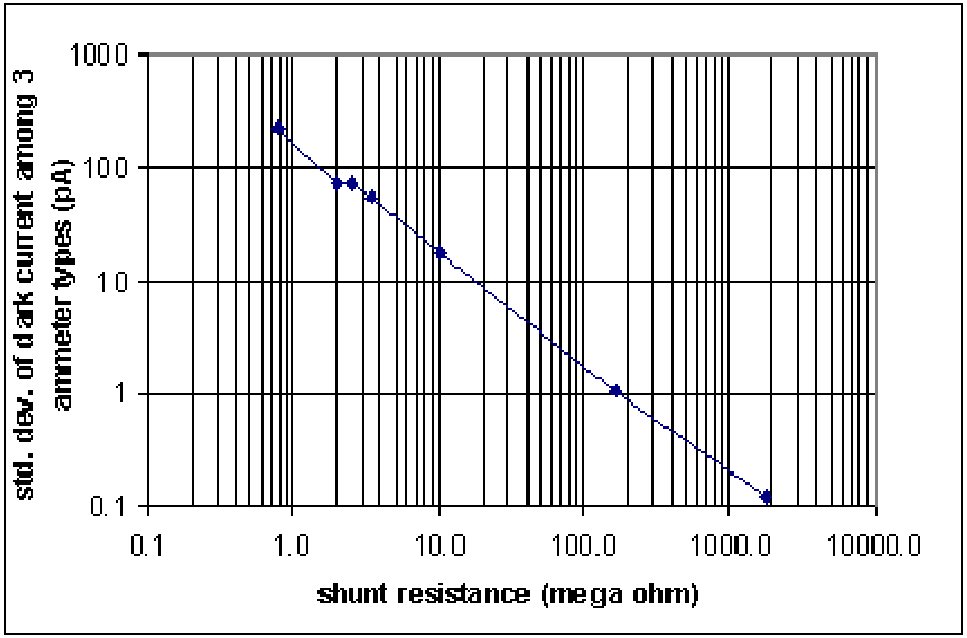
  $R_{sh}$ = shunt resistance

  C = 1e-10 * $A_{active}/t_{active}$ ($\kappa$~12)

  $R_{sh}C$ = 400 ms for 10x10 mm, 25 μm @ 1 GΩ

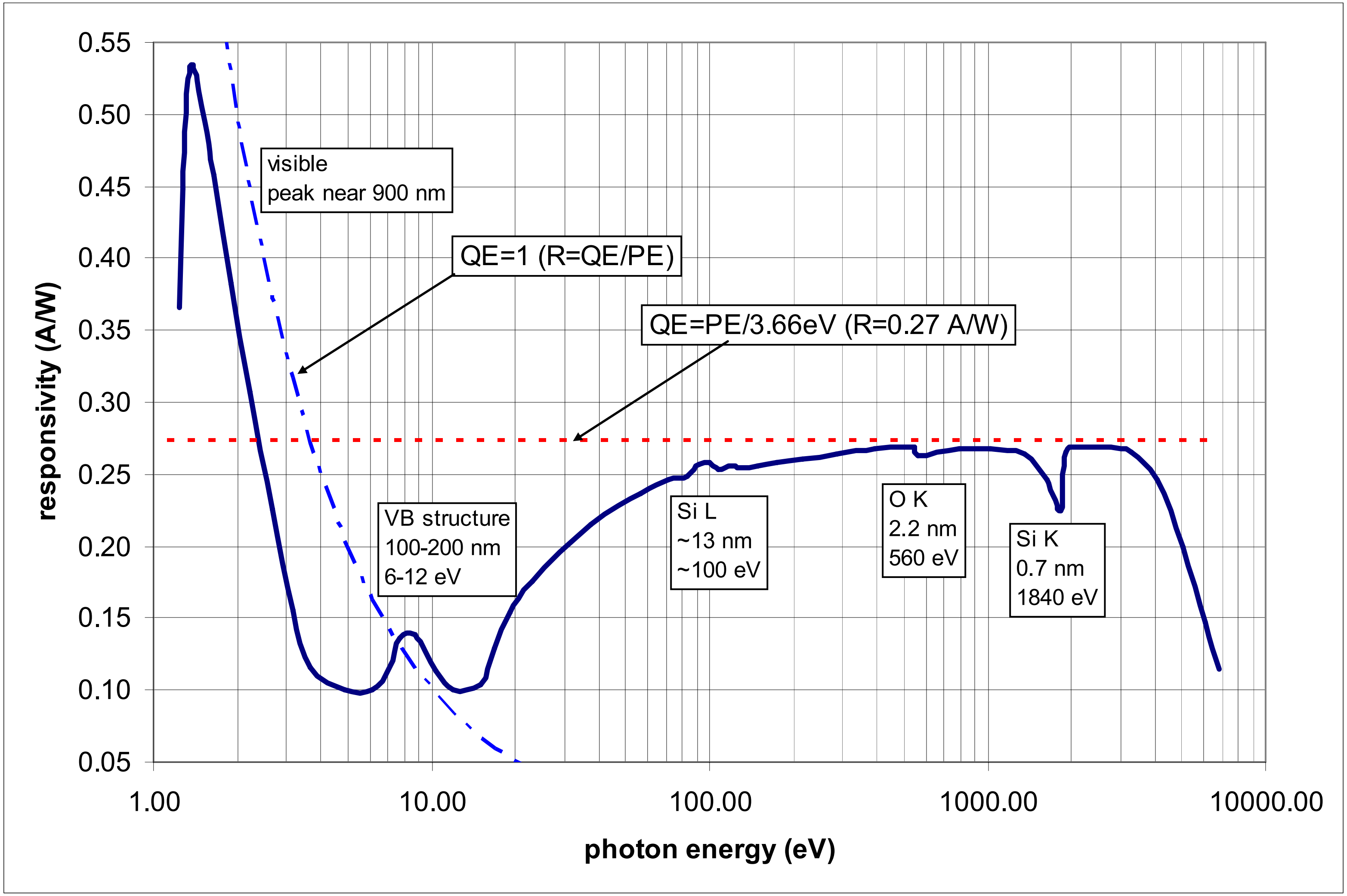
# PD Shunt Resistance vs. dark current




- Can't use dark current as reliable measure of performance UNLESS shunt resistance is 200 M or greater (1 pA accuracy target)
- Lower $R_{sh}$ values give unpredictable results with newly calibrated ammeters of various type

# Typical PD Response



# Self-Calibration

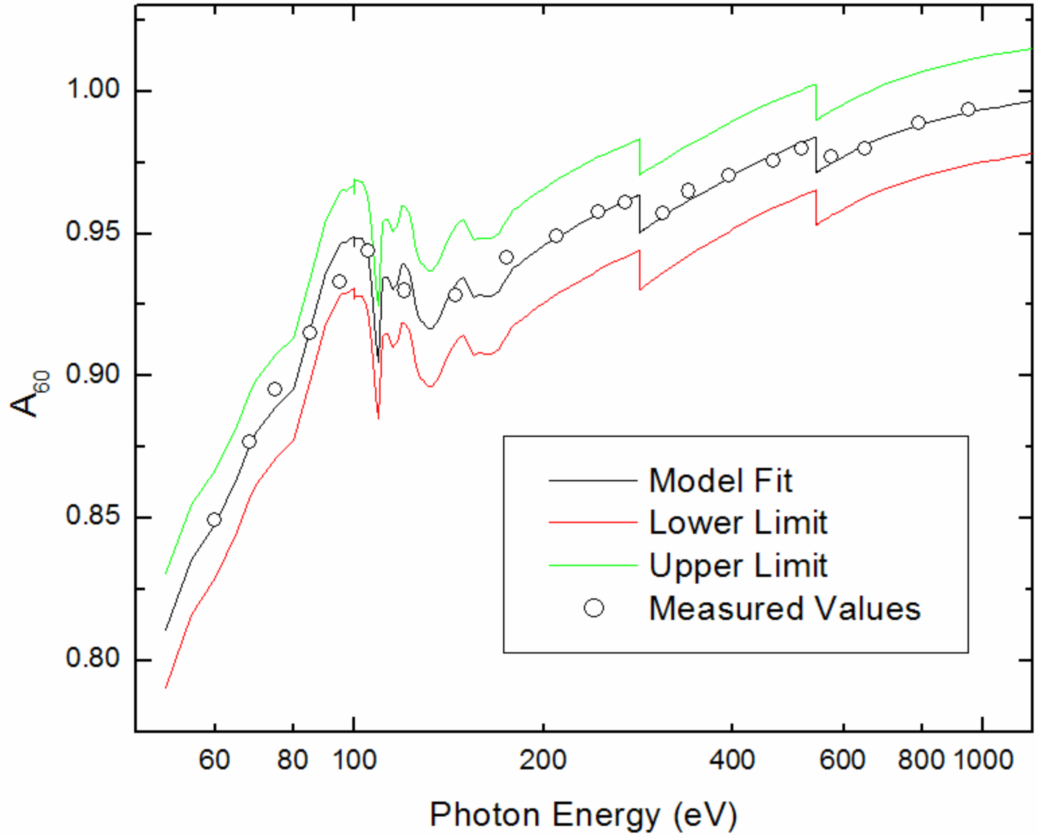
$$S(\phi)=\frac{1}{w}\left\{e^{-\frac{1}{\cos(\phi)}\left(\frac{t_{do}}{\lambda_{SiO2}}+\frac{t_{dc}}{\lambda_C}+\frac{t_{ds}}{\lambda_{Si}}\right)}\left[1-e^{-\left(\frac{1}{\cos(\phi)}\cdot\frac{t_s}{\lambda_{Si}}\right)\Big/\left(\frac{1}{\cos(\phi)}\cdot\frac{L}{\lambda_{Si}}+1\right)}\right]+ss\cdot\left\{e^{-\frac{1}{\cos(\phi)}\cdot\left[\frac{t_{dc}}{\lambda_C}+\frac{t_{do}}{\lambda_{SiO2}}\right]}\right\}\cdot\left\{1-e^{-\frac{1}{\cos(\phi)}\cdot\frac{t_s}{\lambda_{Si}}}\right\}\right\}$$

$S$ = photodiode responsivity
$w$ = mean electron-hole pair production energy
$t_{do}$ = thickness of the silicon dioxide window (dead) layer
$t_{dc}$ = thickness of carbon (dead layer) on the window
$t_{ds}$ = thickness of undoped (or inadequately biased, dead layer) silicon contributing to the window layer
$t_s$ = effective active layer thickness
$L$ = characteristic diffusion length (for photoelectrons released in the back region of the diode)
$ss$ = probability that a hole created in the silicon dead layer will migrate into the active region
$\lambda_{SiO2}$, $\lambda_C$, $\lambda_{Si}$ = x-ray attenuation lengths in silicon dioxide, carbon, and bulk silicon, respectively

$$A_{60}=\frac{S(60^\circ)}{S(0^\circ)}$$

- Ratio response (PD signal current) at two incidence angles
- All parameters but $w$ are determined by this method
- Relies on known optical constants

# $A_{60}$ data and model

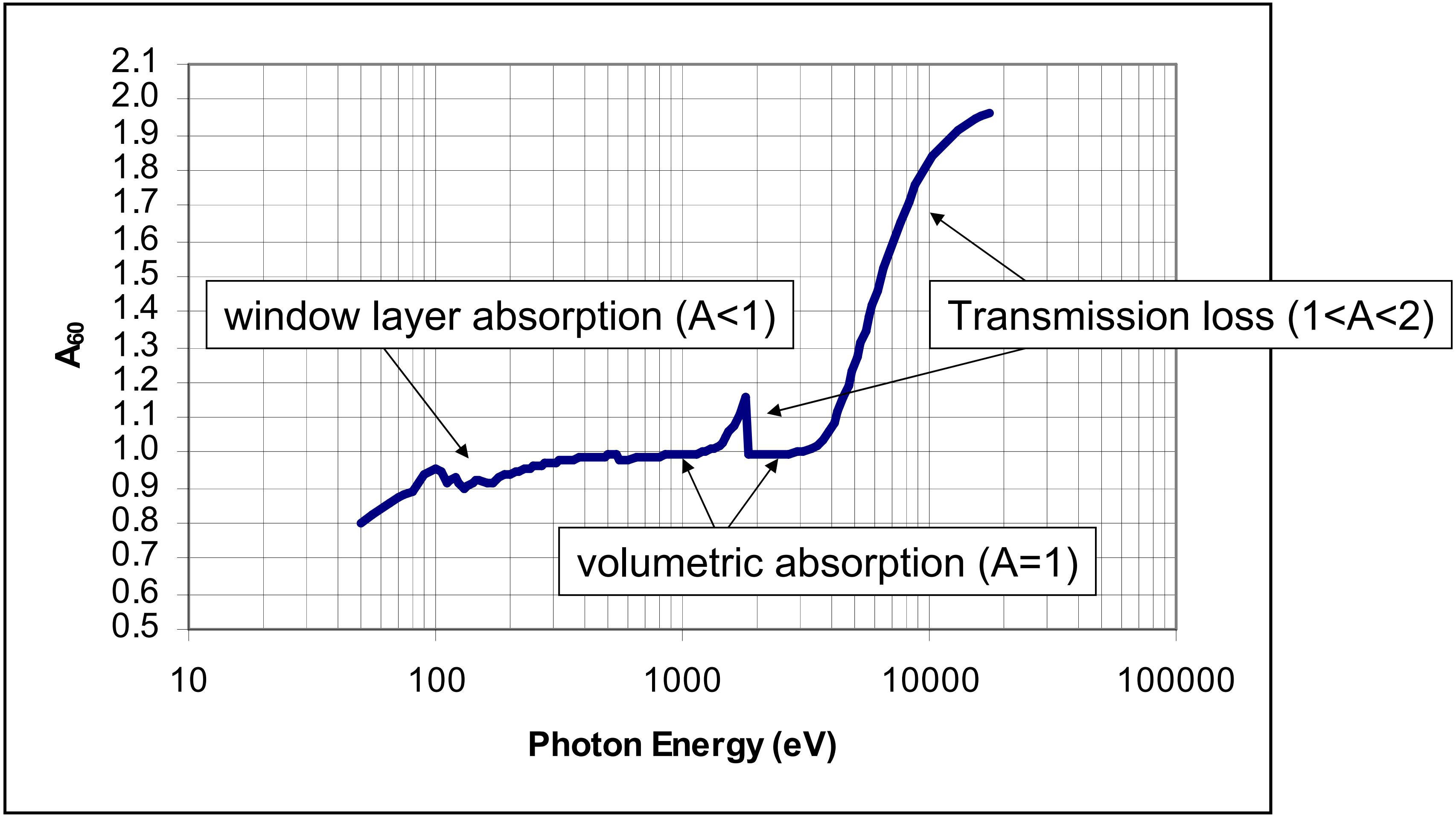



AXUV-100G 02-5 #20
RMS fit error: 2.5%
max error: 1.5 %
Model parameters:
$t_{do}$ = 5 ± 1 nm
$t_{dc}$ = 2 ± 1 nm

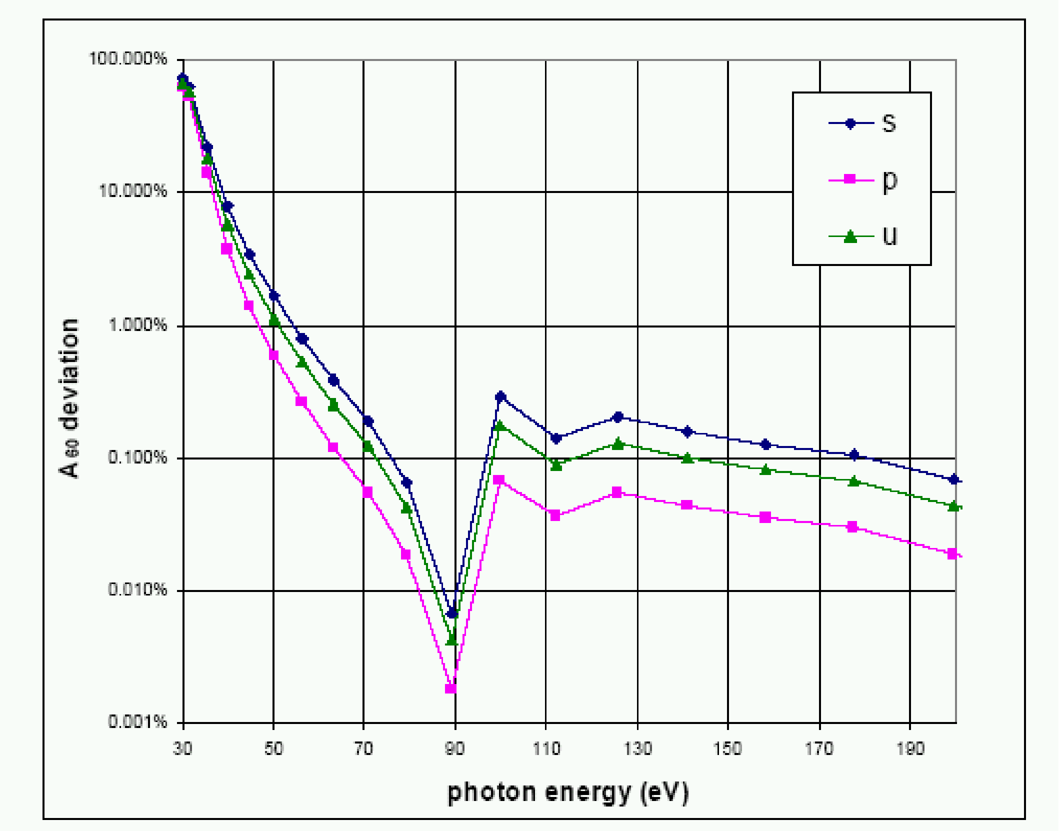
Optical constants from:

- CXRO database (http://www.cxro.lbl.gov/optical_constants/sf/sf.tar.gz)
- For $SiO_2$, CXRO elemental data is taken in stoichiometric ratios above 150 eV
- For $SiO_2$, Below 150 eV, data is used from Rife et al. (Rife, Osantowski, JOSA 70(12) 1513-1518)

# $A_{60}$ model
## with typical parameters



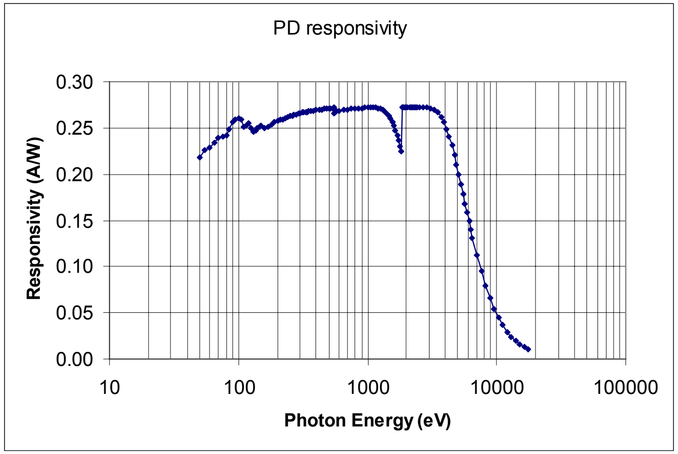
# Reflectivity Limitation

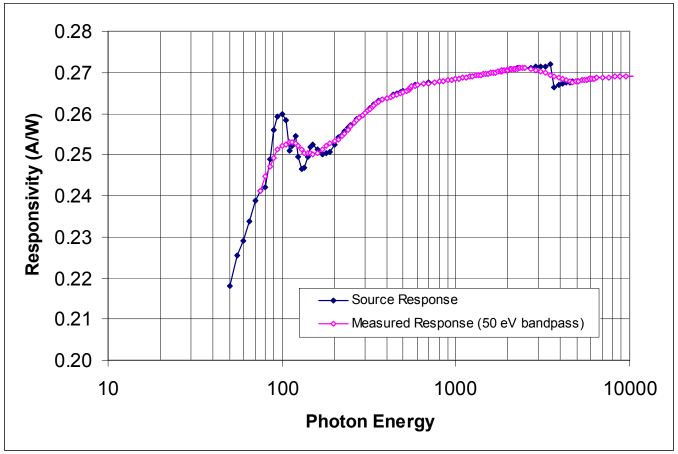



- Reflectivity of silicon at low E reduces absorption at 60 degrees
- To maintain 1% accuracy self-calibration is limited to energies ≥ 50 eV

# Application of PD Response Curve

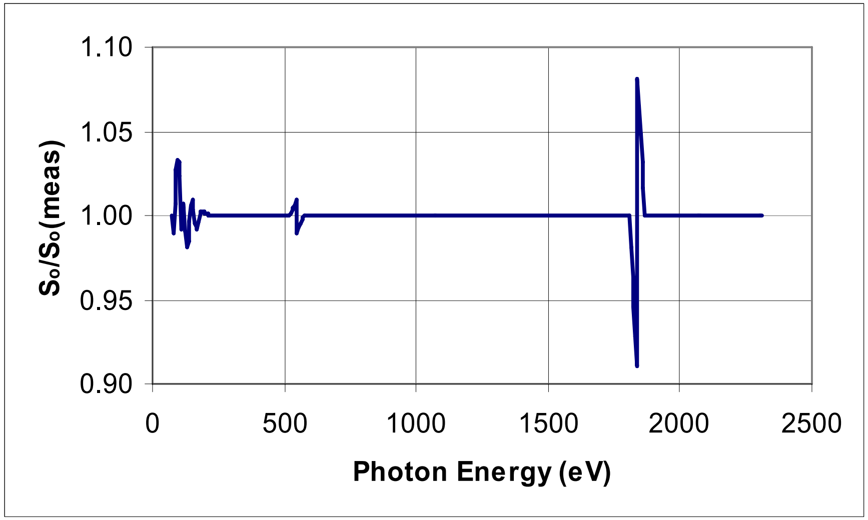
$$S_d(meas) = I_d \cdot \frac{S_\circ}{I_\circ}$$



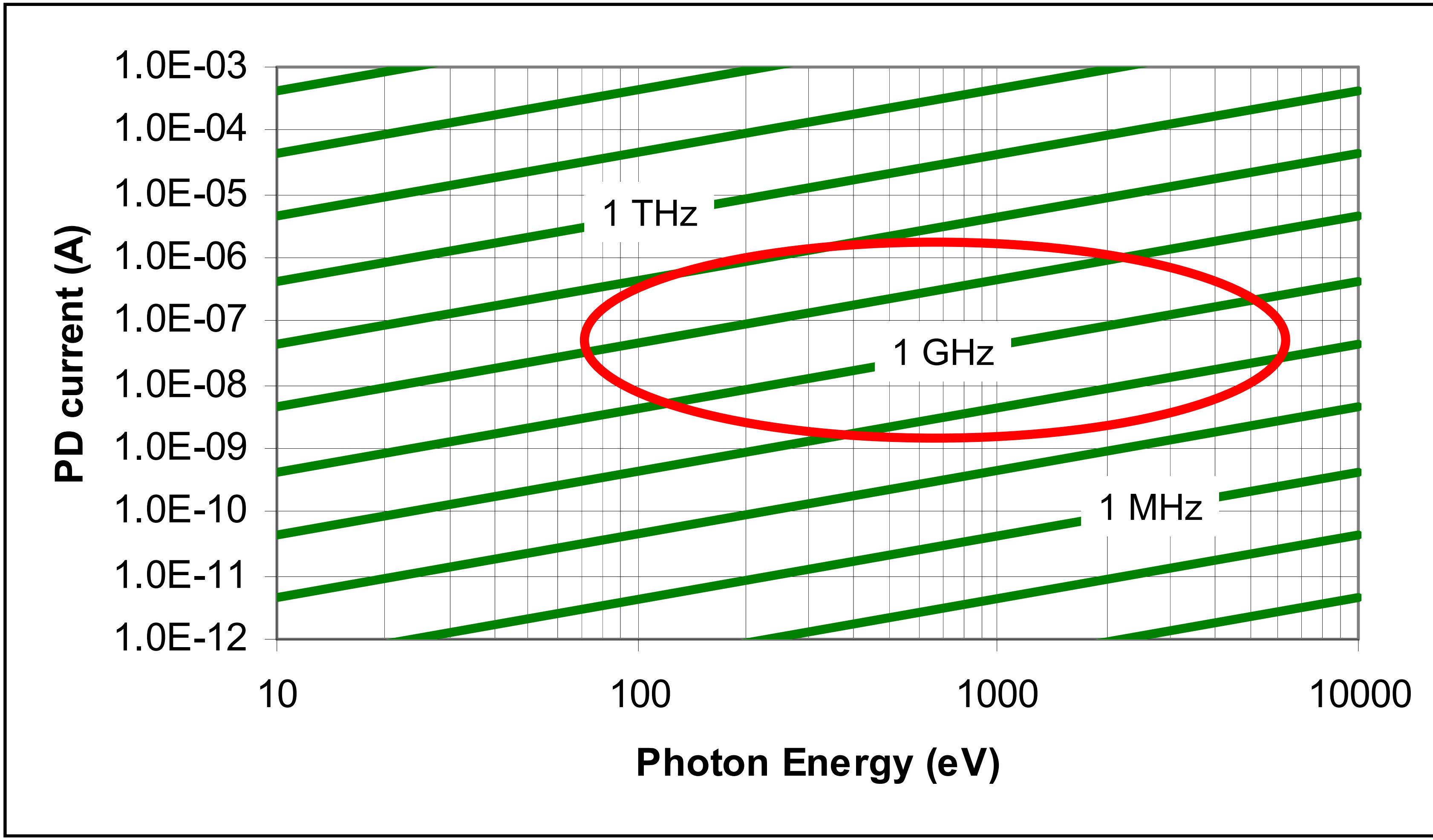




## Application Concerns

- Energy calibration
- Energy resolution
- Harmonic Content



# Silicon PD and Photon Rate



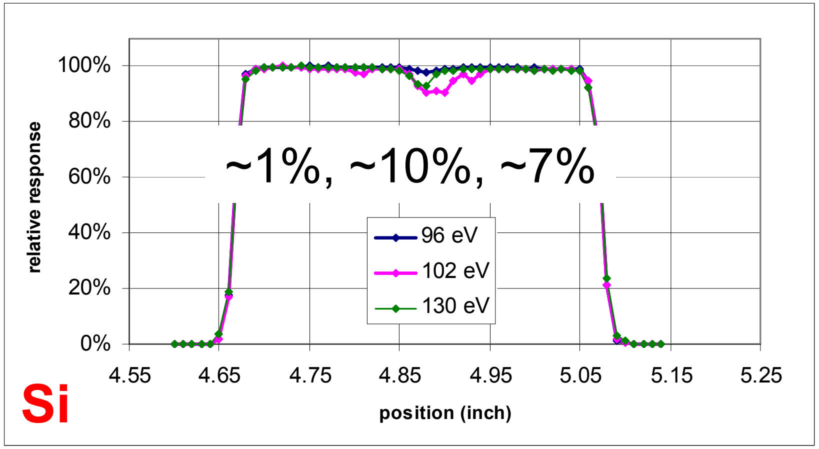
# VUV damage

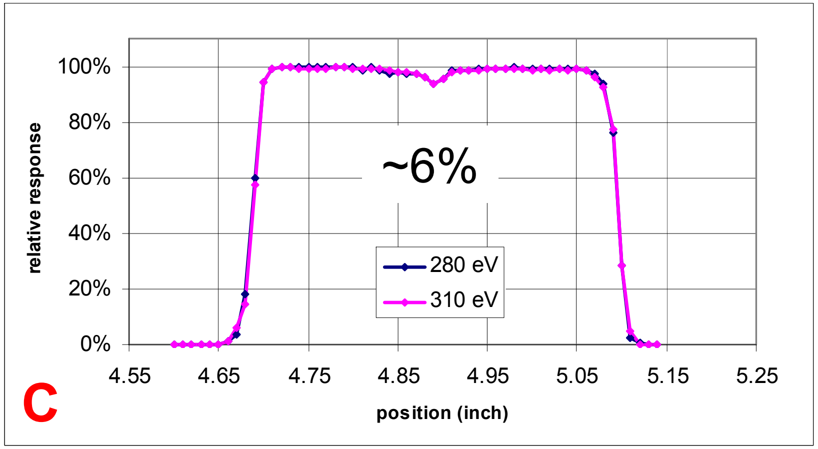
- Not well understood
  - Role of Carbon?
  - Oxidation?
  - Silicon damage / restructuring?
- Exposure limits (~1 year at the beamline?)
- $R_{sh}$ related?
- Self repair?
- Localized affect on responsivity?

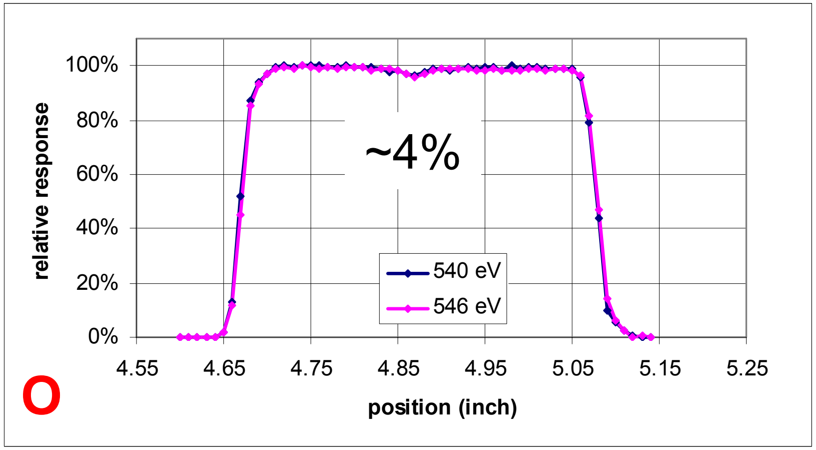
# White Light Damage Study

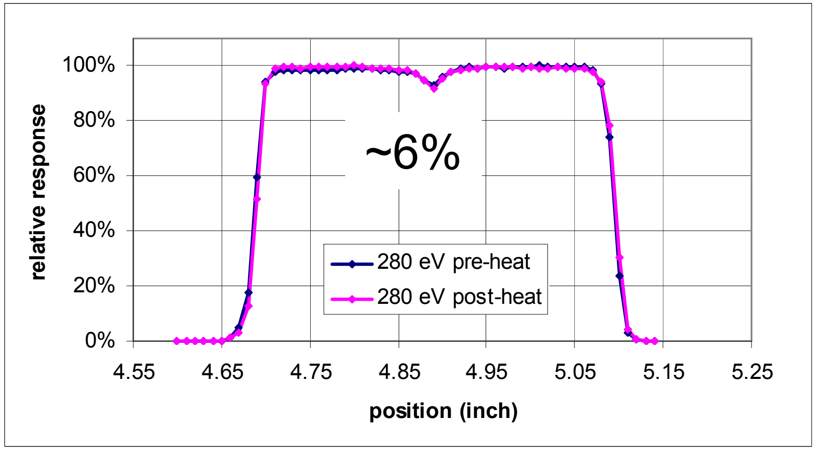
- 4 year (normal operations) equivalent dose in 5 minutes
  - exposure to zero-order beam at beamline U3c
  - 700 μA signal seen during exposure
- Shunt Resistance
  - Initially 19.3 MΩ
  - Finally 17.1 MΩ
- No repair seen after heating to 100 °C

# Damage Study Data



# Damage Observations

- Shunt resistance may be affected
- Silicon appears to play the major role
- No repair behavior seen

- More detailed work desired

# Conclusions

- Si PD is very useful in VUV range, and can be calibrated with minimal effort
  - Chamber must be light tight
  - Use calibration data with care near material edges
  - Photon-counting applications can use PD cross-calibration near the MHz rate
- Important device characteristics are
  - Shunt Resistance
  - Active layer thickness
  - Window thickness / composition
- Diodes don’t last forever